COMPUTER MODELING OF PLASMA FLOW SWITCHES -HIGH CURRENT SWITCHING ON PROCYON*

R.L. Bowers, A.E. Greene, D.L. Peterson
Los Alamos National Laboratory
P.O. Box 1663
Los Alamos, NM 87545

N. F. Roderick**
Dept. of Chemical and Nuclear Engineering
University of New Mexico
Albuquerque, NM 87131

Introduction

Procyon is a high explosive driven pulsed power system designed to drive plasma z-pinch experiments to the 1-MJ level. Details of this system are provided elsewhere in these proceedings[1]. The final switching stage of the Procyon system is a plasma flow switch (PFS). Our most recent experiment (4/29/93) included a full power test of the PFS designed for the Procyon system. In this test the Mark IX explosively driven generator delivered 22 MA of current to the storage inductor. The slight flux compression that occurs in the explosively formed fuse (EFF) opening switch increased this current to 24.5 MA. The EFF then opened and switched 16.5 MA to the PFS. The PFS switched 15.5 MA to the load region (the slot that will contain an imploding foil liner in future experiments) with a 10-90 rise time of 500 ns.

In this present paper we discuss the computer modeling we have done on this Procyon plasma flow switch. In the next section we discuss the design of the Procyon switch and preshot calculations. Although the April '93 experiment was quite successful there were significant surprizes in the performance of the PFS. In the last sections of this paper we discuss the work we have done in understanding the results of this experiment and the conclusions that we have reached to date.

Design and Preshot Calculations

The ability of a plasma flow switch to transfer significant currents (10 MA) to imploding z-pinch loads has been demonstrated in a number of experiments performed on the Shiva Star capacitor bank at the Phillips Laboratory[2]. Data from these experiments were used by us to benchmark the computational tools that we have used to design the Procyon switch. These tools include a 0-D (point mass) model, and 1-D Lagrangian and 2-D Eulerian radiation magnetohydrodynamic (RMHD) codes. This early work demonstrated that our codes could model most aspects of the performance of the Shiva Star PFS. The 2-D RMHD code was also used to design a PFS for experiments fielded on the Los Alamos Pegasus capacitor bank (6.5 MA peak current in the PFS). This work demonstrated the importance of detailed multimaterial modeling of the interface between the switch plasma and the coaxial electrodes. The electrode switch plasma interaction leads to the formation of a plasma boundary layer along the electrode surfaces which consists, almost entirely, of switch plasma. At the load region some of this material can be forced inward onto the load foil, initiating serious, magnetically driven, Rayleigh-Taylor instabilities. In addition, the switch material imploded into the load region carries the current with it and this significantly slows the actual switching of the current to the imploding load.[3]

*This work supported by the U.S. Department of Energy.
**University of New Mexico, Albuquerque, NM USA

This problem of switch material along the inner electrode being accelerated inward onto the load foil proved particularly important at the lower current level of the Pegasus bank. This led to the introduction of a boundary layer trap on the inner electrode which calculations indicated would trap much of the switch material that would otherwise implode in the load slot. This calculational result was verified experimentally.[4]

Early design work for a PFS on the Procyon system, discussed at the last Pulsed Power Conference[5], used a total plasma mass of 150 mg. Subsequent experiments and calculations indicated that a slightly more massive switch plasma would allow more time for current to build up in the coax and would allow more current to be switched to the imploding load if the PFS worked well. Zero dimensional parameter studies put the optimum at about 200 mg. It is worth noting, however, that many parameters in our study were constrained to values close to those that have worked successfully in the past.

Although the study cited in reference 5 involved 150 mg of switch plasma, the reference provides an accurate description of the proceedure we have used to initiate 2-D calculations from 1-D code results. Traditionally plasma flow switches have used plasmas with $1/r^2$ density distributions to match the radial variation of the force due to the magnetic field and obtain uniform acceleration along the coaxial barrel.

We found that when we simulated the performance of a 200 mg PFS with a $1/r^2$ density distribution using our 2-D RMHD code, far too much switch plasma was imploded into the load slot. We attempted to remedy this problem with a boundary layer trap as we had with the Pegasus experiments. However, the total switch plasma in the Pegasus system was 40 mg. In the case of the 200 mg Procyon switch plasma, so much plasma accumulated on the downstream side of the trap that subsequent plasma and current began to be diverted outward. The result was a rapid formation of a alternate current path upstream of the load slot. It was clearly necessary to reduce the amount of switch plasma near the inner electrode. One approach to reducing this mass is to alter the distribution of the mass density with radius.

We performed Procyon preshot calculations with both the conventional $1/r^2$ and a $1/r$ density distributions. In both cases, the mean density, temperature and axial velocity of the plasma were imposed in the 2-D calculation based on values predicted from our 1-D code and then the radial density distribution was imposed with a total mass equal to 200 mg. Figure 1 shows a density snapshot from each of these calculations at 3.9 μs after current first reaches the PFS. The PFS has moved about 4 cm axially during this time. Figure 1a ($1/r^2$ model) exhibits instability growth along the inner and outer electrodes. The initial model contained no perturbations; perturbations are induced by radiative losses at the plasma-electrode interface, and because of 2-D effects associated with the current

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
JUN 1993	**N/A**	**-**

4. TITLE AND SUBTITLE
Computer Modeling Of Plasma Flow Switches -High Current Switching On Procyon

5a. CONTRACT NUMBER
5b. GRANT NUMBER
5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

5d. PROJECT NUMBER
5e. TASK NUMBER
5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
Los Alamos National Laboratory P.O. Box 1663 Los Alamos, NM 87545

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release, distribution unlimited

13. SUPPLEMENTARY NOTES
See also ADM002371. 2013 IEEE Pulsed Power Conference, Digest of Technical Papers 1976-2013, and Abstracts of the 2013 IEEE International Conference on Plasma Science. Held in San Francisco, CA on 16-21 June 2013. U.S. Government or Federal Purpose Rights License.

14. ABSTRACT

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**SAR**	**4**	

flow from the electrode to the back side of the plasma. The rate of instability growth along the inner and outer electrodes are observed to be comparable. Figure 1b (1/r model at the same time) shows the combined effects of gating (the apparent swing of the plasma away from the inner electrode) and instability growth. The effects of gating are also seen in the current rise-time as seen by a magnetic probe placed in the coaxial barrel. For example, probes near the inner and outer electrodes at -4.0 cm in Figure 1a would be expected to see essentially simultaneous response (10-90 rise-time about 50 ns). For the 1/r model in Figure 1b, the rise times would be similar, but it would begin about 100 ns earlier at the inner probe than at the outer one. Gating action along the inner electrode will reduce the mass near there, which will increase the effects associated with magnetically driven instability growth. This is also seen in Figure 1b.

The observations above led to a PFS design which used the combined effects of plasma-electrode instability growth and bulk plasma gating as an opening mechanism. This PFS had a total plasma mass of 200 mg and an assembled density distribution of 1/r. Separately, the aluminum was 130 mg with a $1/r^2$ distribution. The barrier film was 70 mg of polyester with a uniform distribution. A major purpose of the PSS-7 shot, therefore, was to diagnose bulk plasma gating and the formation of an instability that would allow current to break through ahead of the bulk of the plasma, carrying very little switch plasma with it.

Figure 2 shows the density structure of the PFS at three times during its motion down the coaxial barrel. The initial model for this calculation consisted of an all aluminum plasma, 2 cm in axial width, with a 1/r density distribution centered at 0.5 cm. Calculations including a load region (starting at z=-6.5 cm) predicted that the switch plasma would open when it reached the upstream edge of the load region due to a combination of gating and instability growth.

Experimental Results

Details of the experimental results can be found in Reference 1. The most striking feature was that the switch opened much earlier than it should have based on bulk plasma motion down the coaxial barrel (recall Figure 2). A consistent interpretation of this data is that wall induced instabilities along the inner electrode were more pronounced than were the effects of gating seen in the preshot calculations. According to this interpretation, wall induced perturbations set up magnetically driven Rayleigh-Taylor instabilities along the inner electrode which dominate the evolution of the PFS. These instabilities grow rapidly and burst open when the switch plasma has moved less than 3 cm from its original position. Magnetic flux is then transported by low density plasma down the coaxial barrel and into the load region. In effect, switching is complete before the switch plasma has reached the upstream edge of the load. Furthermore, switching is efficient and the switch remains open.

Although this interpretation rests on features seen in the preshot calculations, the timing predicted by the latter does not agree with the data. Evidently, some modification of the preshot model is needed.

Post Shot Analysis and Calculations

Two aspects of the experiment, which differed from the initial design, may have influenced the behavior of the PFS. The first is the current waveform actually seen by the PFS. The measured current rose more slowly for the first microsecond than expected preshot, and then increased more rapidly thereafter. As a result, the aluminum plasma from the graded foil remained in contact with the electrodes longer before assemblying on the barrier film. This increased exposure time can lead to enhanced perturbations at the plasma-electrode boundary. Secondly, the graded foil was badly wrinkled after installation (the amplitude of the wrinkles appeared to be large compared, for example, to the foil's thickness). This pattern of perturbations would be expected to lead to instability growth in the aluminum plasma at least prior to assembly on the barrier film. Differences between the observed and calculated behavior can also be attributed to the initial conditions used for the 2-D simulations. We have found that its behavior is sensitive to whether the initial configuration is represented by an axially uniform plasma, all of which has a 1/r density distribution, or whether it consists of a $1/r^2$ aluminum plasma and a uniform density barrier film.

The masses of the barrier film and graded foil in all of the calculations reported in this section were 66.6 mg and 135.28 mg, respectively. The barrier film was represented by uniform density aluminum, and the plasma from the graded foil had an initial $1/r^2$ density variation. The center of the foil plasma was located 0.6 cm axially upstream of the center of the barrier film. The results were found to be insensitive to the initial axial velocity distribution. The aluminum plasma and the barrier film developed a 1/r density distribution (away from the electrode surfaces) after assembly and about a centimeter's motion down the coaxial barrel. Assembly on the barrier film tends to smooth out some perturbations from initiation time, but the calculations indicate that wall induced perturbations do grow and survive. Finally, all of the results presented in this section used the observed current waveform to drive the PFS.

For the first model (Model A, Figure 3), the axial thickness of the plasma from the graded foil 1.0 μs into current delivery was taken to be 0.3 cm, at a temperature of about 1 eV. After the PFS has moved about 2.5 cm down the coaxial barrel (t=3.75 μs), the instability associated with the wall induced perturbation along the inner electrode has reached the downstream edge of the plasma, and switching begins. However, 100 ns later current flowing along the backside of the switch plasma has imparted an inward velocity to the spike, and begins to close off the gap. This effectively shuts off flux transfer down the coaxial barrel and switching is interrupted. By t=4.2 μs the switch plasma has closed the gap and no further flux transfer occurs. Figure 4 shows the current predicted at three probe locations (z=2.0 cm, 4.0 cm and 5.5 cm) located 0.5 cm above the inner electrode. The uppermost curve is the current drive in the power flow channel. Curve B shows complete switching because the bulk plasma has moved past it; curve C rises rapidly to a current of about 10 MA, and then remains essentially constant until the bulk plasma passes the location of the probe.

Other calculations were performed to investigate the sensitivity of switching to the initial 2-D conditions. In particular, sensitivity to the equation of state and electrical resistivity were examined. The initial velocity profile was varied (uniform axial velocity to the left; expansion velocity about the

aluminum plasma's center of mass; radial velocity gradients near the inner electrode simulating boundary layer flow) but were found to have only a slight effect on the wavelength of the instability and the timing of switching. We also considered the effect of an initial perturbation in the aluminum density within 0.3 cm of the inner electrode. As an extreme example, we reduced the density of the aluminum by a factor of ten within 0.3 cm of the inner electrode (this was intended to simulate the extreme case of a break in the graded foil during vaporization). The results differed only slightly from previous calculations after the assembly stage. All of the variations summarized above resulted in instability growth, rupture of the switch plasma followed by almost immediate reclosing of the switch.

The results of 2-D simulations were found to be sensitive to the initial axial thickness of the aluminum plasma. As the axial thickness of the aluminum plasma increased in the initial model, the tendency for the switch to remain open increased. Models with initial thickness of 0.3 cm, 0.6 cm and 1.2 cm, all having the same total mass, a $1/r^2$ density distribution, and a separate barrier film, were calculated through switching. The 0.6 cm model remained open slightly longer than the 0.3 cm one, but eventually closed. The 1.2 cm model which remained open after switching, is shown in Figure 5. Comparison with Figure 3 shows that the length scale of the instability is larger, but that switching starts at about the same time. By t=4.2 μs, a portion of the switch mass associated with the instability has been shown down the coaxial barrel, eventually impacting the upper electrode. Data from probes located in this region did indicate that full current was not transferred there. Mass from the instability represents a consistent explanation for this observation. Figure 6 shows the computed probe response at axial locations z=2.0, 4.0 and 5.5 cm near the inner electrode, respectively, indicating rapid and efficient switching ahead of the bulk plasma. This model switches at about the right time, and transfers the correct amount of current downstream. The rate of current transfer is a bit slower than in the experiment.

Observations

A comparison of the experimental results and 2-D simulations suggest that the Procyon 1/r PFS may have opened through a combination of wall induced instability growth and bulk plasma gating, in what might be called a plasma instability opening mode. A mechanism of this type may have several advantages as a fast opening switch for plasma load implosions. First, it is rapid, transferring large amounts of current down the coaxial barrel in a fraction of a microsecond. Since the switch opens away from the load region, it may reduce the amount of switch plasma transferred to the implosion load during switching. Finally, because of the reduced time of operation (measured from first current delivery to the graded foil), this type of switch may reduce the amount of electrode material that is radiatively ablated ahead of the switch.

There are several issues which must, however, be resolved before the design is adopted. The principle issue is that of reproducibility, particularly in regard to the instability growth and rupture of the switch plasma. It is also important to establish how sensitive the results are to the details of the initial model. In particular, does the graded foil produce an aluminum plasma with an approximately 1.2 cm axial thickness prior to the assembly stage? Understanding these issues will help determine if this technique can be scaled to higher energy regimes.

References

1. J. H. Goforth, et al., "Review of the Procyon Explosive Pulsed Power System," this conference.
2. J. H. Degnan, et al., "Experimental Results from SHIVA Star Vacuum Inductive Store/Plasma Flow Switch Driven Implosions", IEEE Transactions on Plasma Science, Vol. PS-15, No. 6 December 1987, pp. 760.
3. D. L. Peterson, et al., "Computational Simulations of Plasma Flow Switches and Imploding Loads", Proceedings of the 8th International Pulsed Power Conference, San Diego, CA, June 1991, pp. 614.
4. J. C. Cochrane, Jr., et al., "Plasma Flow Switch Experiments on the Pegasus Facility" Proceedings of the 8th International Pulsed Power Conference, San Diego, CA, June 1991, pp. 618.
5. A. E. Greene, et al. "Computational Modeling of the Trailmaster Procyon System", Proceedings of the 8th International Pulsed Power Conference, San Diego, CA, June 1991, pp. 641.

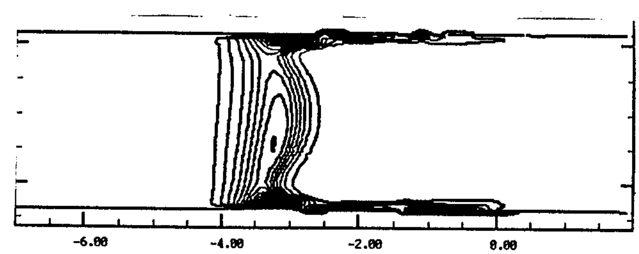

Figure 1a. Calculated density contours of a 200 mg switch plasma which had an initial density distribution of $1/r^2$ (motion here is right to left).

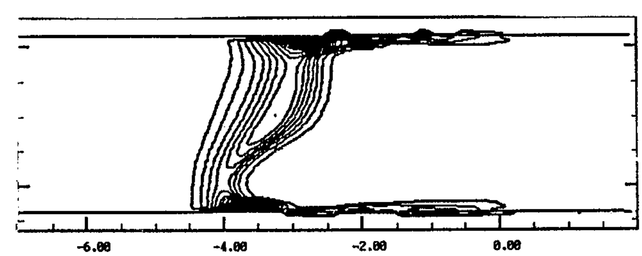

Figure 1b. Calculated contours for a 1/r density distribution for the same time as Figure 1a.

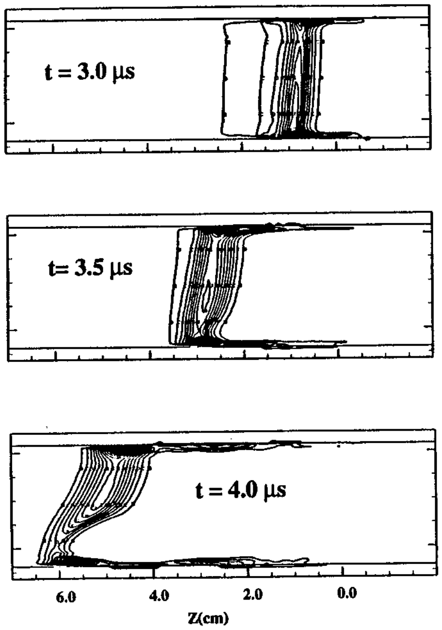

Figure 2. Preshot calculation of density contours for the Procyon PFS at three times during its motion down the coaxial barrel.

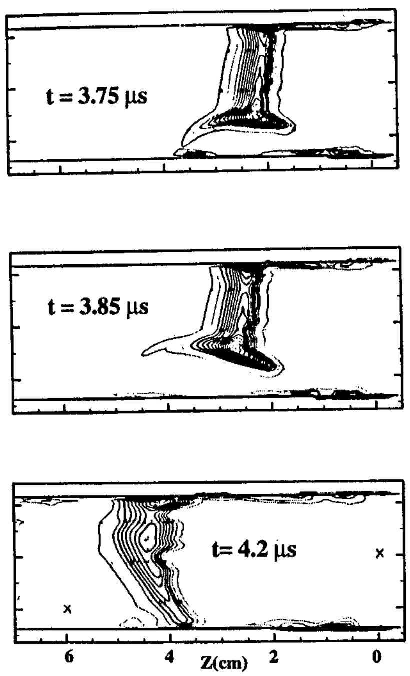

Figure 3. Postshot Calculated behavior of the density contours of the switch plasma using model A (see text). Note that the switch has reclosed by 4.2 μs.

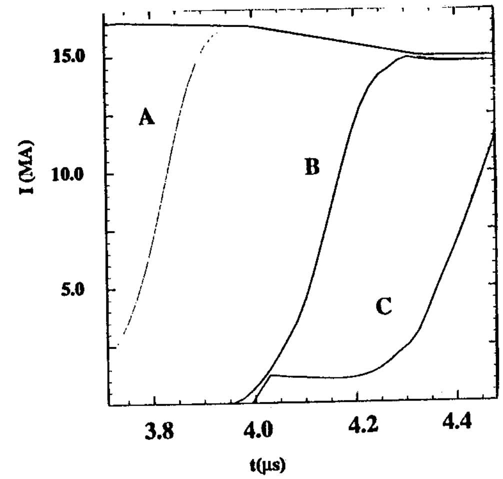

Figure 4. Postshot Calculated time behavior of the electrical current for model A. The three probe locations are 2.0, 4.0, and 5.5 cm along the coaxial barrel, 0.5 cm above the inner electrode.

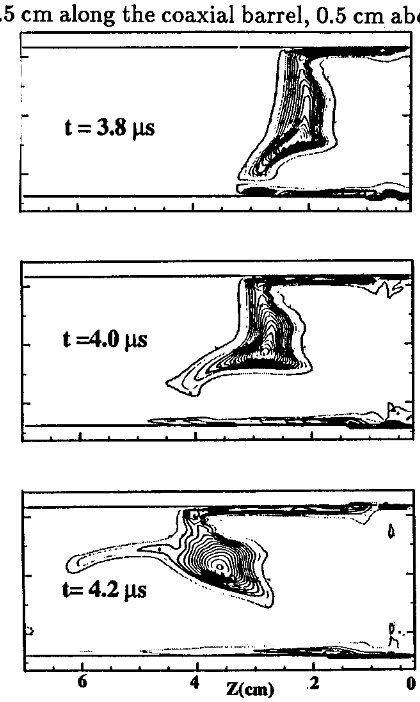

Figure 5. Calculated behavior of the density contours of the switch plasma for model B (see text). Note that the switch remains open.

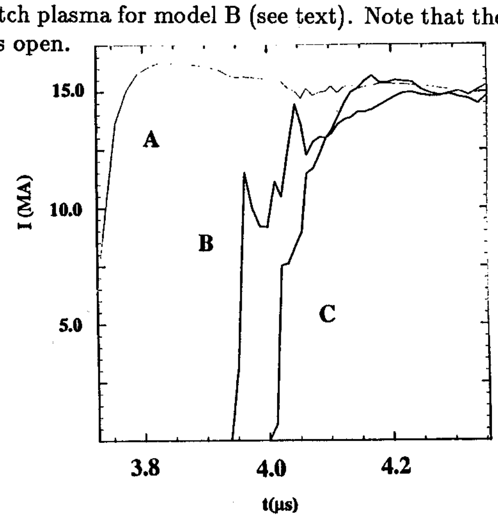

Figure 6. Calculated time behavior of the electrical current for model B. The probe positions are the same as shown in Figure 5.